TIG WELDING OF ALUMINUM ALLOYS FOR THE APS STORAGE RING—A UHV APPLICATION

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May 29, 1996

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INTRODUCTION

The Advanced Photon Source (APS) incorporates a 7-GeV positron storage ring 1104 meters in circumference. The storage ring vacuum system is designed to maintain a pressure of 1 nTorr or less with a circulating current of 300 mA to enable beam lifetimes of greater than 10 hours.[1] The vacuum chamber is an aluminum extrusion of 6063T5 alloy. There are 235 separate aluminum vacuum chambers in the storage ring connected by stainless steel bellows assemblies. Aluminum was chosen for the vacuum chamber because it can be economically extruded and machined, has good thermal conductivity, low thermal emissivity, a low outgassing rate, low residual radioactivity, and is non-magnetic. The 6063 aluminum-silicon-magnesium alloy provides high strength combined with good machining and weldability characteristics. The extrusion process provides the interior surface finish needed for the ultrahigh vacuum (UHV) environment.[2] There are six different vacuum chambers with the same extrusion cross section. The average vacuum chamber length is 171.6". The extruded vacuum chambers are welded to flange assemblies made up of machined 2219 aluminum alloy pieces and 2219 aluminum vacuum flanges from a commercial source.

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ALUMINUM WELDING

The main characteristics of aluminum which influence welding are hydrogen solubility, aluminum oxides, thermal conductivity, thermal expansion, and solidification shrinkage.[3] Weld porosity in aluminum is caused principally by bubbles of hydrogen that form in the solidifying weld pool. The hydrogen solubility of aluminum increases almost twenty times as the material makes the transition from solid to liquid state and continues to increase as the temperature increases (Fig. 1). Hydrogen absorbed during its molten state is forced out of solution as the aluminum cools and changes to its solid state. The hydrogen is trapped in bubbles and cannot effectively be removed from the weld.[4] As the hydrogen comes out of solution, it can be a source of porosity or voids that can connect to form leak paths in a vacuum environment. The molten-solid hydrogen solubility ratio for aluminum is 36 times higher than for iron. This makes aluminum welds much more sensitive to this source of porosity than those of stainless steel.[5] Hydrogen contamination usually comes from moisture or oil (hydrocarbons) on the surface being welded. The parts to be welded must be cleaned well in a detergent bath and dried before welding.

A typical layer of aluminum oxide is 25-50 Å thick. Even if this is scraped away, it will rapidly reform to a thickness of 15Å.[4] Heavy layers of aluminum oxide can act like an insulator, resulting in an erratic welding arc. An aluminum oxide surface is porous and tends to trap moisture and other surface contaminates that lead to weld porosity.[4] Aluminum oxide melts at about 3750 F (2066 C) or about three times the melting point of the aluminum alloy itself.[6] Since the base metal will melt long before the oxides, leaving a heavy oxide layer on the surface before welding can result in inclusions in the solidified weld zone.

The thermal conductivity of aluminum is about six times that of steel.[6] Depending on the alloys being welded and the geometry and thermal mass of the parts, a balance must be met between providing sufficient heat to effect a weld and excessive heat that could lead to distortion and a missed weld joint due to part movement. In the case of the storage ring vacuum chamber flange assembly, the welding electrode was
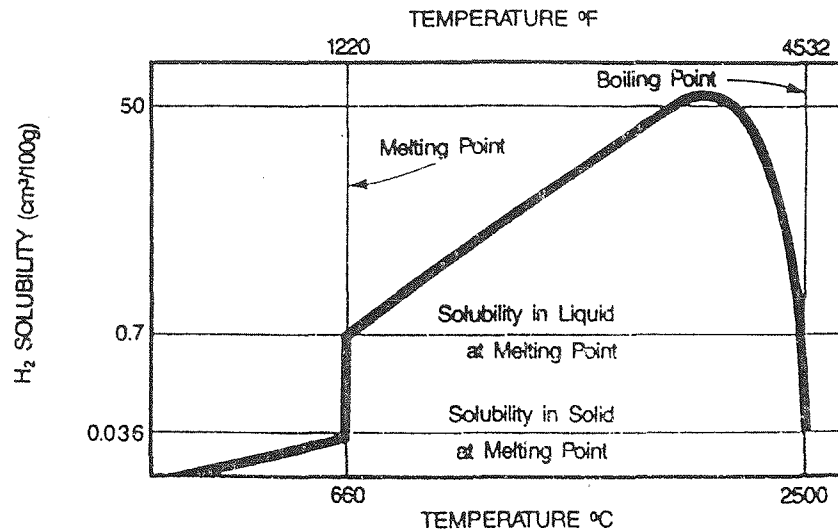
2

Fig. 1 — This graph clearly shows the cause of the bubble-forming process associated with hydrogen absorption. There is almost a twentyfold increase in solubility when aluminum changes to a liquid. Changing back to a solid, absorbed hydrogen is forced out of solution and trapped in the hardening material. (Source: The Aluminum Association.)

Figure 1. Hydrogen solubility of aluminum. (Reprinted with permission of the American Welding Society.)

positioned 0.015" toward the 6063 material in order to compensate for the difference in thermal conductivity between the 6063 (high thermal conductivity) and the 2219 (relatively low thermal conductivity) materials. It was desirable to have the weld fusion zone centered on the part interface. It may also be necessary to provide a water-cooled chill bar, which was required on the welding of the photon beam exit ports to the vacuum chambers. This is a long weld (8 minutes) during which the weld joint would move due to the substantial heat input and the thermal conductivity of the aluminum.

The thermal expansion of aluminum during welding, followed by solidification shrinkage, can result in cracking. Solidification shrinkage in aluminum weld metal is about 6% by volume.[6] Loads imposed by tooling can also play a part in solidification cracks. Weld crack sensitivity can be reduced by appropriate selection of the filler metal. The alloy combination of 2219 to 6063 is highly sensitive to solidification cracking unless the molten weld metal is suitably modified in its composition.[7] The feed rate of the filler wire is also an important variable which must be controlled. For the welding of the 6063 aluminum extrusion to the 2219 flange assembly, a 4043 filler wire was chosen. Typical shrinkage for this weld joint was found to be 0.012" - 0.014".

AUTOMATIC TIG WELDING

The challenge of obtaining UHV-quality aluminum welds can be met with available technology. Careful material preparation combined with proper welding equipment and procedures will yield satisfactory results with aluminum. The arc process selected for the APS storage ring chambers was Gas Tungsten Arc Welding (GTAW), also know as Tungsten Inert Gas welding (TIG). This technique uses heat from an electric arc between a non-consumable tungsten electrode and the base materials to be welded (Fig. 2). Weld purity and cleanliness result because no flux is used that might cause inclusions. A filler metal was required in order to reduce sensitivity to solidification cracking. The equipment chosen, available from a
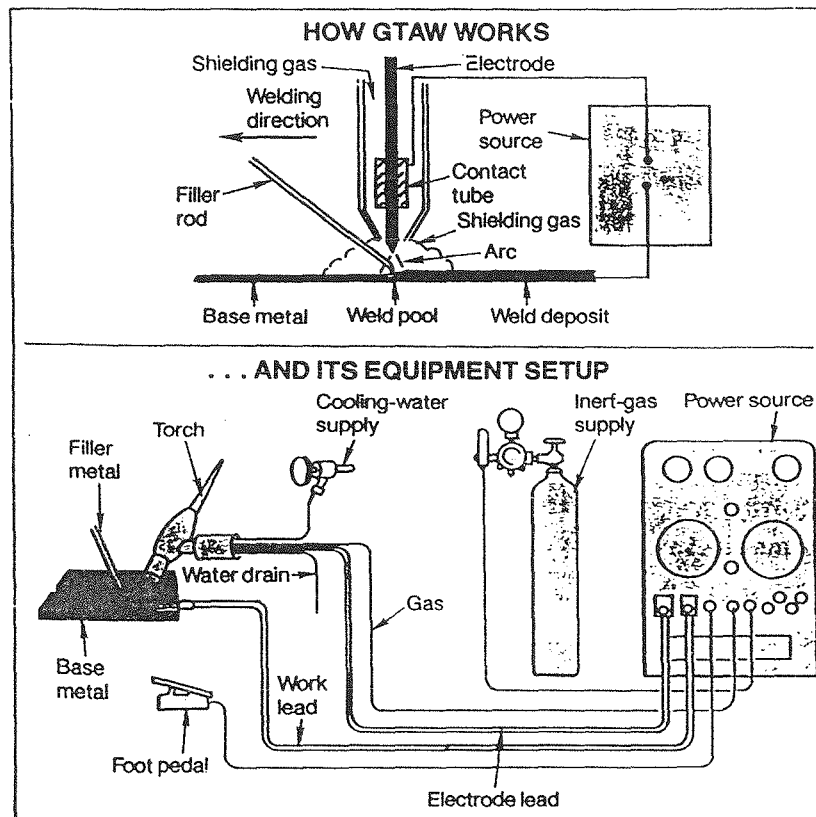
4

Figure 2. Diagram of how gas tungsten arc welding (GTAW) works. (Reprinted with permission of Welding Design and Fabrication magazine.)

commercial supplier, had a proven performance record for reliability and weld quality in similar demanding aluminum welding applications. Multiple machine axis motions were required for several vacuum chamber weld joints having contoured paths. The welding torch position was programmed and controlled through closed-loop servo systems. The welding parameters were integrated with the motion programs, resulting in repeatable settings so necessary in a production environment. All welding parameters (arc voltage, weld current, wire feed speed, and axis velocity) were controlled within +/- 1% of the programmed values by real-time process monitoring. The stability of the welding arc was guaranteed by a stable and responsive Automatic Voltage Control (AVC) head which allowed precise welding torch travel normal to the work while welding, in order to maintain a constant distance between the tungsten electrode and the parts being welded. All of the storage ring vacuum chamber welds were accomplished with a 200 amp power supply, although the system has recently been upgraded to 400 amps.

WELDING THE APS STORAGE RING

TIG welding can be done using AC TIG or DC TIG. For the storage ring vacuum chamber, DC TIG was chosen because it results in better penetration welds with a smaller Heat Affected Zone (HAZ) due to less heat input to the metal. DC TIG is also well suited to the automatic welding process. The use of inverter power supplies is often considered when welding aluminum. The variable polarity operation fluctuates between electrode-negative (straight) polarity and electrode-positive (reverse) polarity. The electrode-negative operation enhances penetration and narrows the weld bead while the electrode-positive polarity provides a cathodic cleaning action on the aluminum.[8] The APS welding systems do not have inverter controls. Instead, each joint was hand-scraped immediately before welding to remove the heavy oxide layer. Cleanliness must be a high priority to obtain UHV-quality aluminum welds. Equally important is the design of the weld joint. General guidelines that should be followed when designing welded vacuum vessels include:

1. Weld from the vacuum side if possible;

2. Use full-penetration welds if welding must be done from the atmosphere side;

3. Avoid gas-trapping, close-fitting surfaces that are not part of the weld zone.

Figure 3 shows the joint design for the vacuum chamber end flange assemblies to the aluminum extrusion. This was a full-penetration DC TIG weld requiring 3-axis contoured motion from the atmosphere side. There are 470 of these welds in the storage ring. The thickness welded was approximately 0.180". Underbead penetration into the beam chamber geometry was limited to 0.020" for rf impedance reasons. As discussed earlier, it was necessary to offset the tungsten electrode towards the 6063 extrusion in order to completely consume the joint interface in the weld zone.

Figure 4 shows a 4.5" aluminum Conflat welded to both sides of the photon extraction channel of the extrusion. The top flange is for the insertion of a photon absorber; the lower flange mounts an ion pump intended for the local gas load due to the absorber. Similar features are found on each of the aluminum chambers of the storage ring. This "butt joint" was welded from the inside (vacuum side) with full penetration. Note that the end of the flange weld neck was turned to a smaller diameter. This was done for two reasons: 1) to provide accurate machined surfaces of the parts being welded, and 2) to allow for a full-penetration weld without putting excessive heat into the material, resulting in deformation. It was also necessary to control heat input on all of the vacuum welds near a Conflat flange. The flange temperature could not exceed 150 degrees C to avoid tempering and loss of strength at the Conflat knife edge. Note the circumferential groove adjacent to the joint interface. This was done in all cases to better match the thermal masses of the different aluminum alloys being welded and to allow visual inspection of the weld underbead by the machine operator.

The photon beam exit ports have a joint design similar to the end flanges. There are two exit ports per sector, one for insertion device (ID) radiation and one for bending magnet (BM) radiation. The ID exit port requires a 58"-long linear weld on both sides
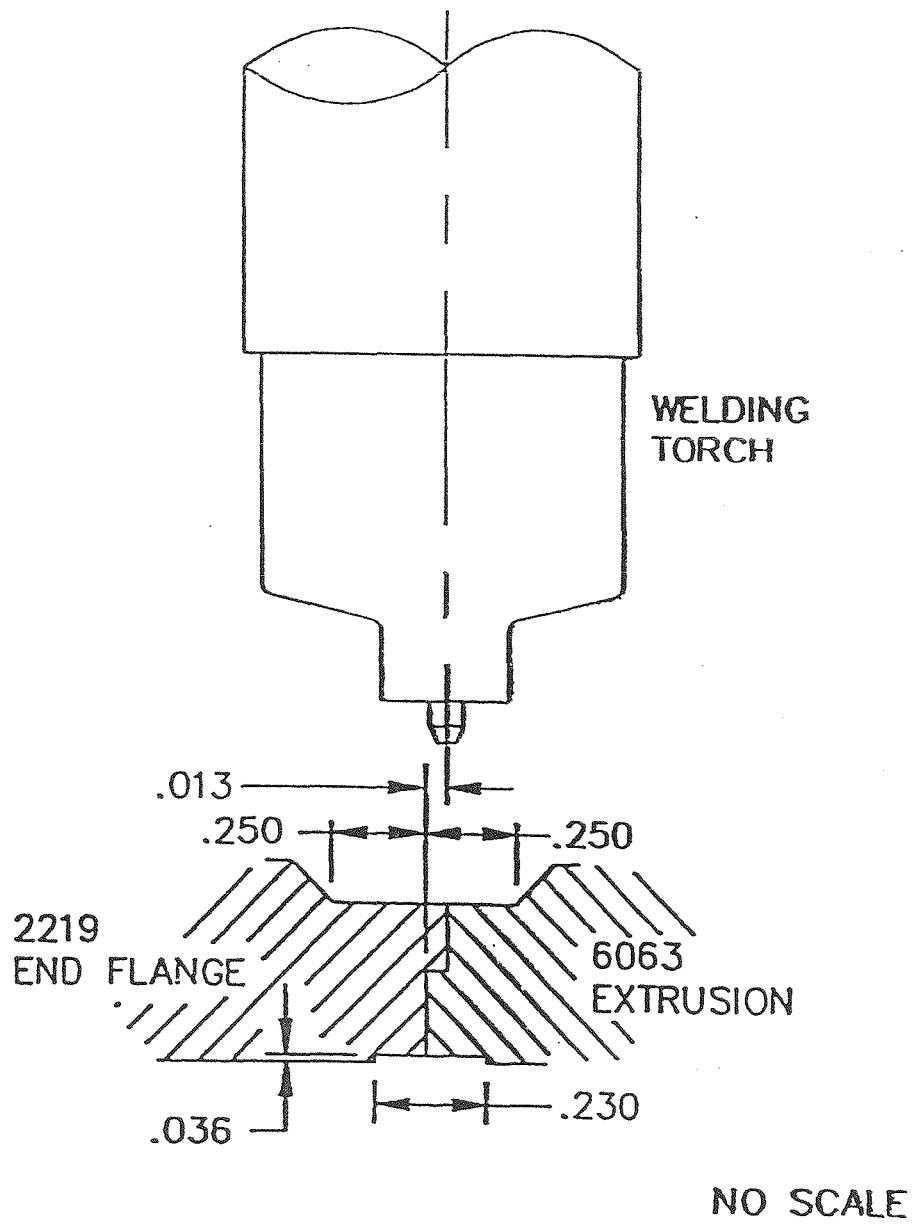
Figure 3. Vacuum chamber to end flange assembly.

Text labels visible in figure:

WELDING TORCH

.013

.250   .250

2219 END FLANGE   6063 EXTRUSION
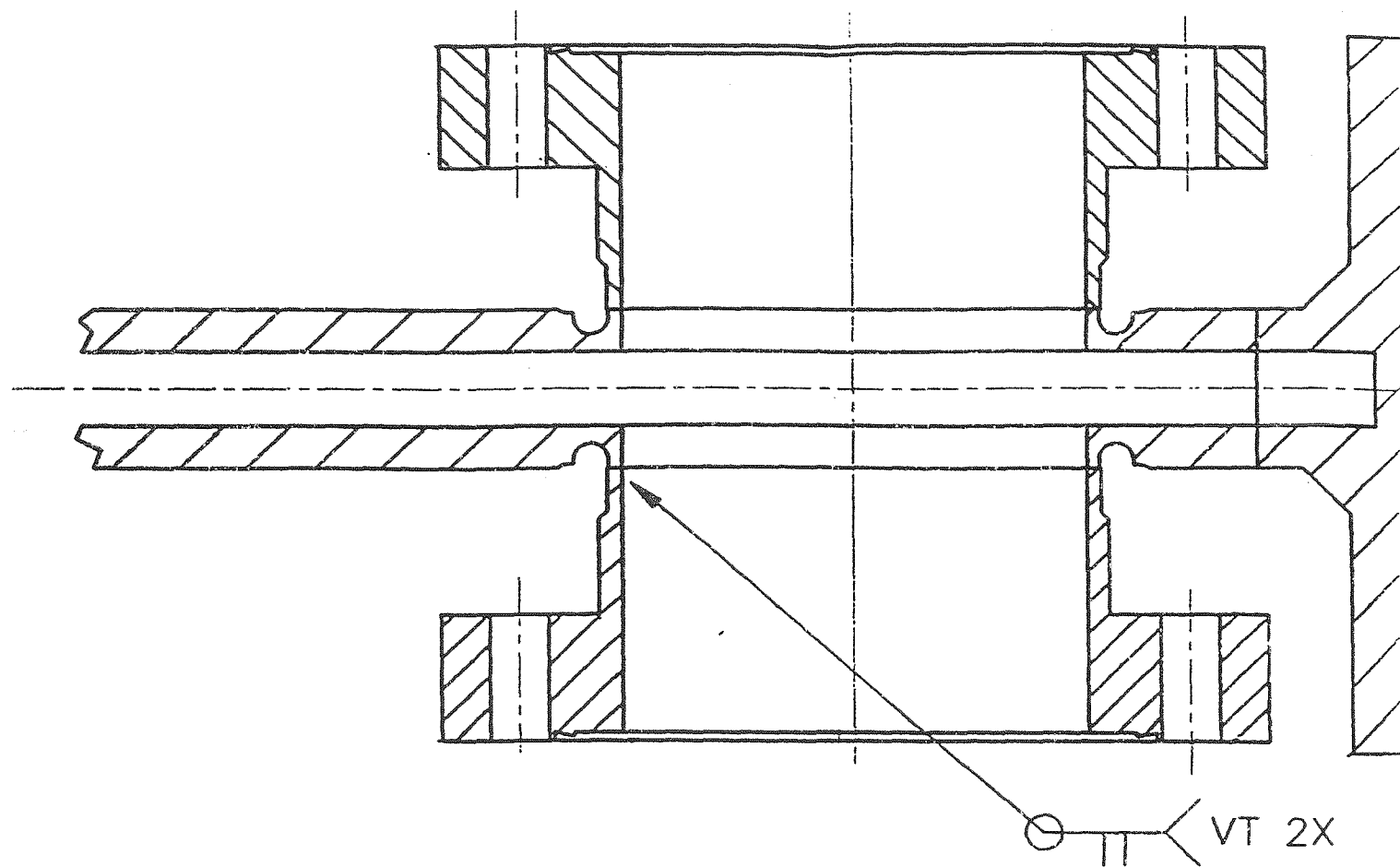
.036   .230

NO SCALE

Figure 4. Vacuum chamber photon channel to Conflat flange.

of the interface to the chamber, while the BM exit port requires a 73"-long linear weld. These are full-penetration welds done from the atmosphere side. Because of the long length to be welded, substantial heat is absorbed by the aluminum extrusion during welding. Water-cooled chill plates were clamped to the extrusions in order to limit the movement of the weld joint off of the pre-programmed torch electrode path. Incomplete fusion of the joint would result in a virtual leak at the least, a real leak at the worst. It was necessary to view the electrode path while welding via a television monitoring system. The machine operator had the ability, through a hand-held pendant, to input machine axis corrections in real time in order to keep the welding torch centered on the joint. This system was available from a commercial supplier and was integrated with the automatic welding machine.

QUALITY ISSUES

There are approximately 2500 aluminum welds in the APS storage ring that must provide reliable UHV integrity during machine operations. Several of the joint designs are common to each of the six different vacuum chambers, resulting in 13 different machine welding programs. Achieving high reliability with a minimum amount of rework was a quality goal set early during the welding development program. The use of automatic welding systems was a step in the right direction. The requirement in design for full-penetration welds was also an early decision with quality implications. A full-penetration weld can be readily inspected visually and, while not a complete guarantee of weld quality, a complete penetration of the weld joint for the full length of the interface allows a 95% confidence level that the weld is suitable for a UHV application. Complete inspection must include radiographic analysis, i.e., x-raying, against a standard. However, there is no known published standard for TIG welding of aluminum vacuum vessels. At the APS production facility, MIL-STD-2219 for Class A welds was adopted. This was the toughest specification against which APS aluminum welding performance could be judged. The main requirement concerns

subsurface pores and inclusions (as seen in x-ray photographs) relative to weld thickness (T) as follows:

1. Individual size must be less than 0.33T or 0.060", whichever is less.

2. Spacing (of inclusions or pores) must be at least 4 times the size of the larger adjacent imperfection.

3. Accumulated length (of inclusions or pores) in any 3" of weld must be less than 1.33T or 0.24", whichever is less.[9]

Ten percent of the storage ring vacuum chambers were subjected to x-ray inspection against MIL-STD-2219, Class A, throughout the production period. No rejects against this standard were found. After some initial start-up problems, the repair rate for the entire 235 vacuum chambers was approximately 3%. No chambers were scrapped as a result of a welding problem. Repairs were all done with manual TIG welding which was found to be more efficient than setting up the chambers a second time on the tooling of the automatic systems.

This level of production performance was the result of high quality standards employed during cleaning, welding, assembly, and vacuum leak testing. Cleaning of the aluminum vacuum chambers has been well documented by others.[10] Assembly was performed in a clean room. Each vacuum chamber was leak tested by pumping with turbo pumps, ion pumps, and NeG strip activation, with two thermal cycles to 150 degrees C. On achieving a certification pressure of 2×10^{-10} Torr or better, the chamber was considered acceptable for use in the APS storage ring.

There were numerous quality standards demanded of welding system ancillaries. The weld filler wire was purchased "shaved," i.e., drawn through a die that removes surface oxides and inclusions just prior to the wire being wound on a spool and hermetically sealed. The wire spool container on the welding machine had inert gas constantly purged through the wirefeed system. The 75% helium/25% argon shielding gas used from a bulk supply was ultrahigh purity gas (99.999%) and was constantly monitored at the machine gas box for moisture content. Additionally, the welding machine control provided quality assurance through data logger software, which

collects actual welding parameters from feedback systems, displays it against preset values, and provides a hard copy for reference.

WELD INTEGRITY TESTING

Two 6" aluminum Conflat-to-transition-piece weld assemblies were destructively tested as a means to further validate the automatic welding process. They carried production tracking numbers 4607 and 4618. These were production pieces having a butt-welded joint geometry similar to most of the joint designs on the storage ring vacuum chambers. The two assemblies were x-rayed and found to be acceptable. They were then leak tested to 1.3×10^{-11} atm cc/s helium and passed. Then both assemblies were thermal cycled to 150 degrees C using heat tapes and held at that temperature for 10 minutes. The temperature was then ramped down to ambient using a water chiller. Each thermal cycle required approximately 90 minutes. Both assemblies were subjected to 50 cycles.

Assemblies 4607 and 4618 were then leak tested again and passed. Then both were x-rayed again; no changes were found when compared to the films taken previously. Each assembly was then cut up into 12 pieces for metallographic examination and labeled 4607-1 through 12 and 4618-1 through 12. An independent lab was used for metallographic evaluation of the 24 samples. The results indicated that one sample, 4607-1, showed two discontinuities (micropores). All other samples showed no discontinuities, including cracks, microcracks, or inclusions, as per MIL-STD-2219, section 5.4.4, Weld Quality.[11] The 24 samples were finally tensile tested, with the results shown in Table 1.

Table 1: Results of Metallographic Evaluation

	4607			4618	
No.	Actual (lbs)	Theo. (lbs)	No.	Actual (lbs)	Theo. (lbs)
-1	1000	1400	-1	1175	1500
-2	850	1500	-2	1150	1312
-3	425	562	-3	1125	1312
-4	1675	1312	-4	1325	1500
-5	1450	1312	-5	1000	1312
-6	1575	1312	-6	1625	1500
-7	1725	1218	-7	1500	1400
-8	867	1312	-8	1750	1312
-9	1700	1500	-9	1750	1500
-10	875	1125	-10	900	1500
-11	1625	1500	-11	2150	1400
-12	2050	1400	-12	2450	1640
Total	15625	15453		17900	17187

NOTE: Theoretical tensile strength based on 25,000 psi ultimate yield strength for 2219 aluminum calculated for area of sample specimen.

ACKNOWLEDGEMENT

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